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Instrumental Sensing of Stationary Source Emissions

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16. ABSTRACT

Remote sensing methods offer a number of advantages over contact measurement methods in the area of enforcement and surveillance of emissions from stationary sources. Several techniques have been developed that can measure the gas concentration, effluent velocity, and particulate opacity. The velocity measurement is needed so that a mass emission rate may be determined. To evaluate the accuracy, utility, and state of development of some of these techniques, a series of measurements were conducted at coal-burning power plants in which the results of the remote measurements were compared with the results of in-stack measurements made using EPA Reference Methods. The techniques studied and the properties measured were (1) infrared gas-filter correlation radiometry (SO_2), (2) Fourier-transform spectroscopy (SO_2), (3) ultraviolet matched-filter correlation spectroscopy (SO_2), (4) infrared and ultraviolet correlation (velocity and SO_2), (5) infrared laser Doppler velocimetry (velocity), and (6) visible lidar (plume opacity). The techniques used, procedures, the measurement results, and recommendations for evaluating and using remote sensing instruments for measuring emissions from pollutant sources are described.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
*Air pollution *Remote sensing Sulfur dioxide Plumes *Optical measuring instruments *Evaluation		13B 14B 07B 21B

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Instrumental sensing of stationary source emissions

Ground-based, remote sensing techniques are under development and testing

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Instrumental remote sensing methods have been used for air pollution measurements for over a decade. Various techniques such as long-path, open-path infrared spectroscopy have been used [illegible] to identify and measure the concentrations of various pollutants in the atmosphere. In recent years the development of a number of electro-optical techniques for remote measurement of the concentration of pollutants emitted by stationary sources has been undertaken by EPA. Most of these techniques have evolved from laboratory methods that have been in use for many years.

For stationary source applications, it is likely that remote sensing will find its greatest use in enforcement and surveillance activities. It is also possible that at a large industrial complex, where there are many pollutant sources within a single plant boundary, the use of remote sensors for continuous monitoring could be practical. The particular advantage of a remote sensor over a contact sensor in these applications is its ability to monitor a number of different sources (dispersed) in a relatively short time. In enforcement activities, where a single remote sensor could be used to monitor several sources per day, it is estimated that operational costs would be one-tenth the cost of contact sensors, although the initial cost of the remote sensor would probably be significantly more than that of the contact sensor. Other advantages of remote sensors for enforcement purposes are that they can monitor emissions on an unannounced and noninterfering basis from off the source property, and most of the sensors can operate at night as well as during the day.

A variety of programs have been conducted within EPA over the past several years to evaluate the capability of various ground-based remote-sensing techniques for measuring the SO_2 concentration, velocity, and opacity of effluents from coal-burning power plants.

Measurement programs

Several techniques have been developed that can measure the concentration and velocity of gaseous species and particulate opacity. The velocity measurement is needed so that a mass emission rate may be determined. In order to evaluate the accuracy, utility, and state of development of some of these techniques, a series of measurements have been conducted at coal-burning power plants, and the results of the remote measurements were compared with the results of in-stack measurements made using the EPA Reference Methods. The techniques tested in these programs are:

☐ Ultraviolet gas-filter correlation radiometry (GFCR), for SO_2 concentrations

☐ Fourier transform infrared spectroscopy (FTIS), for SO_2 concentrations

☐ ultraviolet [illegible] correlation spectroscopy ([illegible]), for SO_2 concentrations

☐ Infrared and ultraviolet [illegible] ([illegible]), for velocity and SO_2 concentrations

☐ Infrared laser Doppler velocimetry (LDV), for plume velocity

☐ visible laser radar (lidar), for plume opacity.

The emphasis in the work described on measurements of gaseous pollutant concentrations has been on techniques not requiring lasers because of overall practicality. For remote velocity and opacity measurements, techniques using lasers are necessary.

GFCR technique is able to measure SO_2 concentrations in the 400-ppm range with an accuracy of about 10% as compared with Reference Method 6 for a plume 4 m thick at a temperature of about 500 °C. The present instrument does become inaccurate if any of the parameters—pathlength, concentration, or temperature—drop much below the above values. The GFCR is an ideal remote sensor in that one person is able to operate the instrument and reduce the data, and the instrument's cost is not excessive (about $60,000). Furthermore, the overall performance of the instrument can probably be significantly improved through the use of cooled detectors, more efficient optics, and better calibration procedures. The technique is readily adaptable to other gases such as CO, HF, and HCl.

FTIS is probably capable of yielding greater accuracy than the GFCR if a reliable plume temperature can be determined. However, instrument cost, complexity of data reduction and complexity of operation are much greater for the FTIS than for the GFCR. Since most pollutant monitoring is done on a single-pollutant basis, the GFCR must rate well ahead of the FTIS in overall practicality for enforcement needs. If needs arise where multipollutant monitoring becomes important, the FTIS could become more practical.

For general research studies to characterize gaseous pollutants emitted by various types of sources and to determine optimum spectral regions for the operation of specialized instruments (for example, the GFCR), an FTIS system will remain the most suitable spectroscopic method. This type of research activity is being conducted at EPA; the grating spectrometer used in the past has been replaced by an FTIS coupled to telescopic optics. The system is mounted

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Measurement sites

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Figure 1

Operational modes of remote sensing

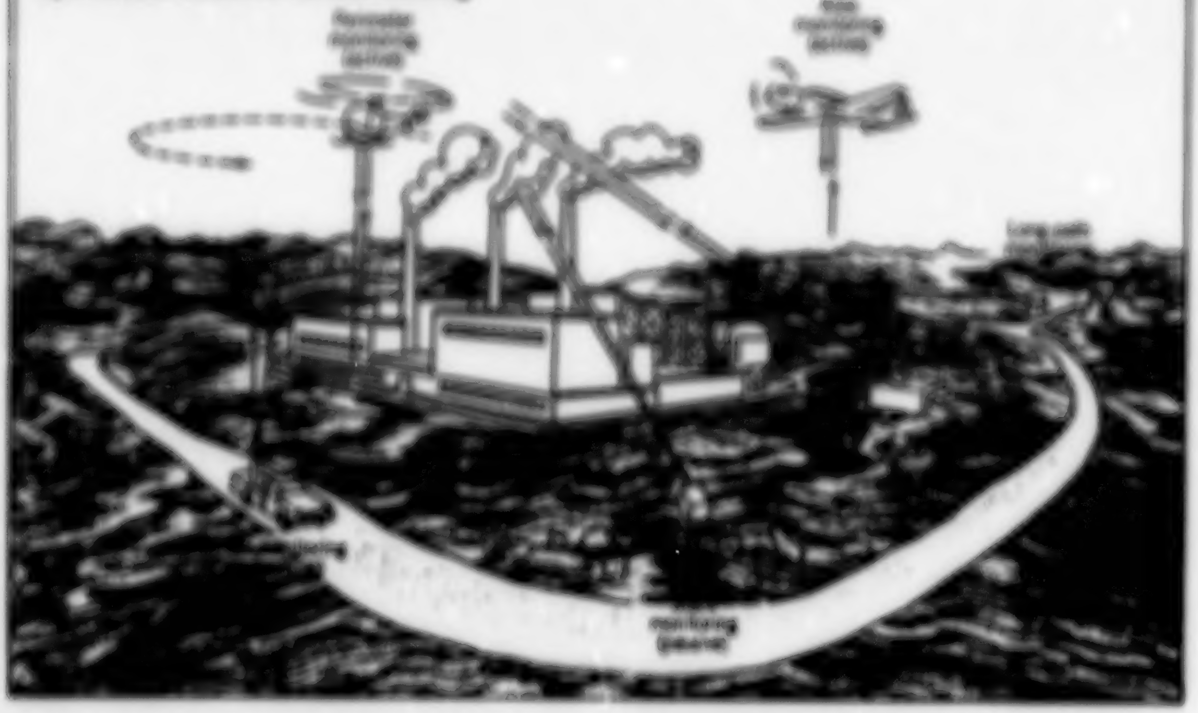

Perimeter monitoring (active)
Area monitoring (active)
Long path monitoring
Tracking
monitoring (passive)

TABLE 1

Summary of selected remote sensing techniques

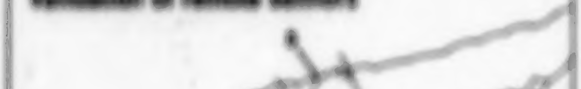
Technique & [illegible]	Spectral region	Species & parameters	Scale	Comments
Active techniques				
Differential absorption	UV, VIS, IR	Many gases	Stack, area & perimeter	Preliminary field testing under way. Complicated and expensive but can provide complete 3-dimensional
Lidar	VIS	Opacity	Stack & area	Operational day & night for plume. Area unit being developed
LDV	IR	Velocity	Stack & perimeter	Operational day & night for plume. Has potential for mass fluxes
Long-path absorption	UV, VIS, IR	Many gases	Area & perimeter	[illegible] dispersion or [illegible] systems, path limits, double-ended
Raman	UV, VIS	Many gases	Stack	May not have enough sensitivity
[illegible] Raman	VIS, UV	Some gases	Stack	Lab tested only; has increased sensitivity over plain Raman
Fluorescence	UV, VIS	Many gases	Stack	Limited sensitivity and specificity
Passive techniques				
Correlation [illegible]	UV, VIS	SO_2, NO_2	Stack & perimeter	Commercially available; day time operation only
Gas filter correlation	IR	SO_2	Stack & perimeter	Stack instrument field tested. Area instrument under development. Day & night use. Potential for many gases
Photographic	VIS	Opacity	Stack	Needs further development
[illegible]	UV, IR	SO_2 and velocity	Stack	Needs continued development and evaluation
[illegible]	IR	Many gases	Stack & area	Lab tested only; field testing planned
[illegible]	IR	Many gases	Stack	Requires high-resolution grating or interferometer instrument for sensitivity and temperature data

the pollutant optical depth (product of concentration and path length) in a vertical column surrounding the stack. These data, coupled with the local wind velocity, allow calculation of a mass emission rate. This type of perimeter measurement is especially applicable to extended area sources, but the validation is most accurately done on a single isolated stack.

Most of the measurements described in the article were conducted at the River Bend Steam Plant of Duke Power Company near Charlotte, N.C. At this four-unit, 600-MW, coal-burning power plant, the EPA Emissions Measurement and Characterization Division, with the cooperation of Duke Power Company, conducts many of its instrumentation test and evaluation programs. One stack at this plant is fitted with a number of ports to allow attachment of various cross-stack and extractive monitoring systems. The semipermanent equipment includes a Lear Siegler Model RM 4 transmissometer to measure opacity and a Du Pont Model 460-1 continuous extractive analyzer for SO_2 and NO_2.

FIGURE 2

Measurement locations for validation of remote sensors



The remote measurement site at Duke Power is about 400 m slant range from the top of the instrument stack; the line-of-sight is about 6° above the horizontal. Most of the remote measurements are made from this site, but other sites are also used. The ports on the instrument stack are between 1–3 m above the plant roof level. There is a ladder to the top of the stack to permit "S"-type measurements. A small building has been assembled on the plant roof near the instrumented stack to house instrument recorders and to serve as a site laboratory. When plant operating conditions permit, the generating load can be varied to change the effluent exit velocity and selected precipitator sections can be shut off to increase plume opacity. In this way the effect of these known changes on the operation of the remote instruments is determined.

Measurements

The **GFCR instrument** was developed for EPA by Science Applications, Inc. The instrument's operating principles are indicated in the simplified schematic (Figure 3). Plume radiation traverses the two pairs of optical channels and is focused onto an infrared detector after being spectrally filtered and optically chopped at a carrier frequency of 800 hz (ω_c). The filter is centered at 2500 cm^{-1} and has a bandwidth of about 25 cm^{-1}. This particular configuration is optimized for SO_2 concentration measurements.

[illegible] infrared radiation from plume passes alternately through [illegible] correlation cells [illegible] the detector. Plume SO_2 radiation is [illegible] by the SO_2 in correlation cell [illegible] signal produced by the detector that depends on the plume SO_2 [illegible] with SO_2 concentrations and temperatures. In the other channel the correlation cell contains a different amount of SO_2 and thus will produce a different signal [illegible] the detector [illegible] plume SO_2. These signals are separately amplified and their ratio calculated. The calculated signal is a function of plume SO_2 concentrations, and the instrument is calibrated by determining this ratio as a function of known SO_2 concentrations in a heated cell. The ratio technique has the advantage of essentially eliminating the temperature dependence of the resulting signal.

Preliminary field data obtained with the GFCR in the fall of 1975, along with comparison data from EPA Reference Method No. 6 and the [illegible] extractive analyzer. The GFCR results were within about 15% of the Reference Method results.

Since the completion of the measurements described above, one problem has occurred with the GFCR instrument: the correlation cells containing SO_2 have shown a tendency to leak over long periods of time (several months). It has not yet been determined whether the leaks result from interaction of the SO_2 with the sealant that bonds the sapphire cell windows to their quartz body or possibly just failure of the sealant. This is not now felt to be a major problem, since cells of more recent design have shown much greater stability. The first model of this instrument lacked sensitivity; a new model is now being evaluated. This new model uses telescopic optics and liquid-nitrogen-cooled detectors to increase sensitivity by about two orders of magnitude.

The use of FTIS in laboratory emission or absorption spectroscopy is a well-established technique. A block diagram of the system used for remote-sensing measurements is shown in Figure 6. The interferograms produced in the field by the interferometer were processed by a real-time analyzer to ensure that the entire system was operating properly. Tape-recorded interferograms were later processed on a large computer to produce high-resolution spectra for analysis. In addition to recording spectra of plume emission, calibration spectra of blackbody radiation, the sky background, and the atmospheric attenuation between the plume and the FTIS were also obtained. (The EPA-owned FTIS system allows complete data processing in the field.)

The principal problem in calculating a species concentration from its emission spectrum is that the temperature must also be determined from that spectrum to be a truly remote technique. This is a difficult calculation since an error of just 5% in the temperature will lead to an error of 15–40% in SO_2 concentration for the 4 μm band at 400 °K. This situation essentially prohibits the use of any simple data analysis technique.

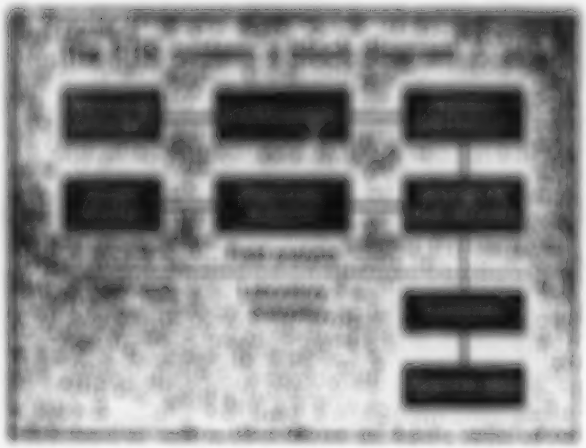


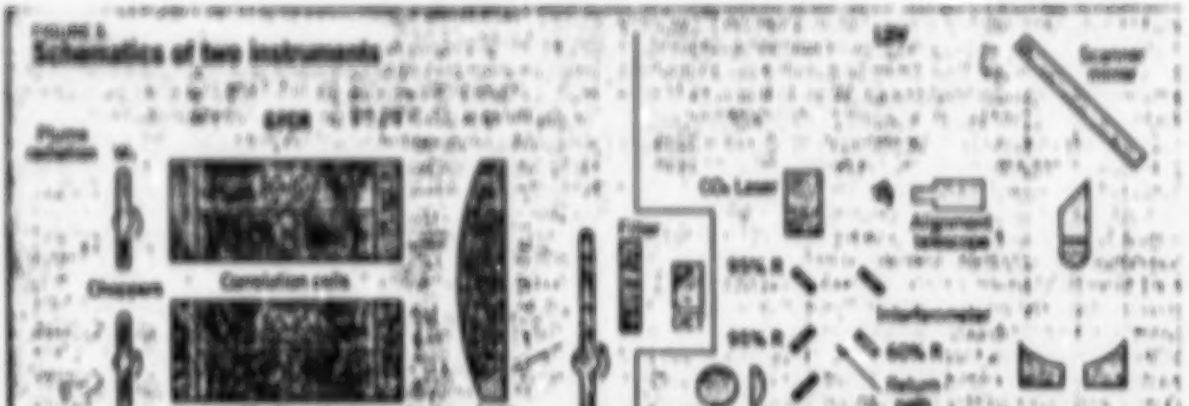
FIGURE 6
The FTIS system: a block diagram

The details of the FTIS measurements were previously reported (see Herget, W. F., Report to EPA, Contract 68-02-1804, 1976). In the preliminary calculation of SO_2 concentration, the temperature was determined by measuring the separation between the P and R branches of the SO_2 band. This method gave results in considerable error. A second temperature measurement was based on the strength of CO_2 radiation from the plume and a knowledge of the CO_2 concentration in the plume. This method gave much better results; however, a number of assumptions were made, and it is not certain that the results could have been obtained without a prior knowledge of the plume characteristics.

Considerable work has been done toward the goal of analyzing plumes remotely by using an FTIS. There is no question that the FTIS is the most suitable instrument for obtaining high-resolution spectra of stack emissions for species identification purposes. In previously reported work (see Additional reading, Prengle et al., 1973), a temperature measurement determination was based on the total energy content in the central burst of the interferogram. The method was shown to work reasonably well on particulate-free plumes, but no measurements were made on plumes containing appreciable amounts of particulates.

The first instrument developed especially for remote sensing of SO_2 emissions from power plant plumes was the correlation spectrometer (COSPEC) developed by Barringer Research. This instrument measures the ultraviolet attenuation of SO_2 in plumes; scattered sunlight serves as the source of UV radiation. The

FIGURE 5
Schematics of two instruments



[illegible] uses a small grating spectrometer to produce an SO_2 spectrum at the exit slit, where a mask (the "correlation mask") matched to the structure of the SO_2 bands in the 0.3-µm region alternately transmits peaks and valleys in the SO_2 spectrum to a detector.

The COSPEC instrument is used most effectively in an "up-looking" perimeter mode. In this mode, the SO_2 optical depth is measured in a conical volume surrounding the source in question. By also measuring the local wind velocity, the SO_2 mass emission rate from the source may be calculated.

An evaluation of this type of measurement is most accurately done where there is a single stack serving as the source. This situation does not exist at the Duke Power Plant site, and a site was selected in the Southeast where a coal-burning plant was operating with a single stack. From measurements taken there, it was found that the COSPEC and instack mass-emission rate measurements agreed to within ±20%. The wind velocity measurements were considered to be a major source of error in these measurements. (Wind velocity was determined by tracking a pilot balloon with a theodolite.)

During August, 1975, a UVTV system developed by Dr. Reginald Exton of NASA's Langley Research Center and an IRTV system developed by Mr. Edward Cross of Aerospace Corporation were both operated at the Duke Power Plant site. The UVTV produces a visible picture showing the attenuation of scattered solar UV energy by plume constituents; the plume appears darker than the bright sky background. The IRTV provides a visible picture of the infrared radiation from warm plume constituents; the plume appears brighter than the cool sky background.

The UVTV was shown to be able to measure SO_2 concentrations with an accuracy of ±25% if the plume is relatively clean (opacity <20%). The data are obtained by filtering the camera first at 0.34 µm, where particulate opacity is measured, and then at 0.31 µm, where particulate opacity plus SO_2 opacity is measured. From these two measurements, the SO_2 attenuation can be determined and the concentrations calculated. Calibration is obtained by sighting the TV camera through cells that contain known amounts of SO_2. The IRTV is not able to measure SO_2 concentration because of a lack of spectral resolution and knowledge of the plume temperature.

It was anticipated that both systems would be able to measure the plume velocity, with the IR system having the advantage of being able to operate at night. The velocity was calculated by measuring the time required for gradients in the plume to travel a known distance, by using successive frames from the videotaped TV picture. The velocity determined in this manner was about a factor of two less than that determined from instack measurements. The assumed explanation for this is that the observed gradients are caused by the mixing of ambient air with the edges of the plume. Such a situation would be expected to produce a velocity somewhere between that of an ambient air and the true plume velocity. It was observed that the TV velocity did track the instack velocity in a regular manner during periods of velocity change, and thus it may be possible to demonstrate a consistent empirical relationship. Work in this area is continuing.

Since emission standards for stationary sources are generally based on a mass-emission rate, it is necessary to measure effluent velocity as well as concentration by remote methods to take full advantage of remote-sensing techniques. The LDV (Figure 3) technique has been in use for about 10 years to make non-contact velocity measurements in experiments concerning wind tunnels, clear-air turbulence, wake vortices and atmospheric winds. The principle of operation is simple. A CO_2 laser beam is propagated through the atmosphere and brought to focus at the desired range. Aerosols in the atmosphere scatter a fraction of the laser energy back toward a receiving telescope. Since the aerosol particles are in motion, backscattered energy will be shifted in frequency from the outgoing laser beam because of the Doppler effect. The shift in frequency depends on the laser wavelength and the velocity component along the laser beam. The backscattered energy and a fraction of the outgoing laser beam fall on the same detector, and the difference in the frequency is detected by conventional heterodyne techniques.

In order to determine the feasibility of remotely measuring stack effluent velocity by LDV, a program was undertaken using an existing LDV system at the Duke Power Plant site. Measurements were conducted in August, 1975 and January, 1976, and the results have been described in detail by Miller and Schwiesow (1976) (see Additional reading). Although the primary aim of the program was to demonstrate the feasibility of the remote velocity measurements, a secondary aim was to determine what, if any, relationship exists between the intensity of the backscattered signal and the attenuation coefficient of the plume (as determined from the opacity of the plume). It was shown that a reasonably linear relationship exists between plume attenuation coefficient and mass density for a given type of particulate source. Thus, the LDV measurement, utilizing a single instrument, has the potential to give a mass-emission rate for particulates.

Analysis of the velocity measurements found the LDV values within 14% of the instack values obtained by using EPA Reference Method 2. Since Reference Method 2 is considered accurate to ±20%, the agreement is about as good as might be expected. Although only two sets of data relating backscatter signal strength to plume attenuation coefficient were obtained, there is certainly good indication that a linear relationship exists. This relationship, if verified by additional measurements on a variety of sources, would allow a single LDV instrument to be used to measure a particle mass-emission rate when calibrated for a particular type of source.

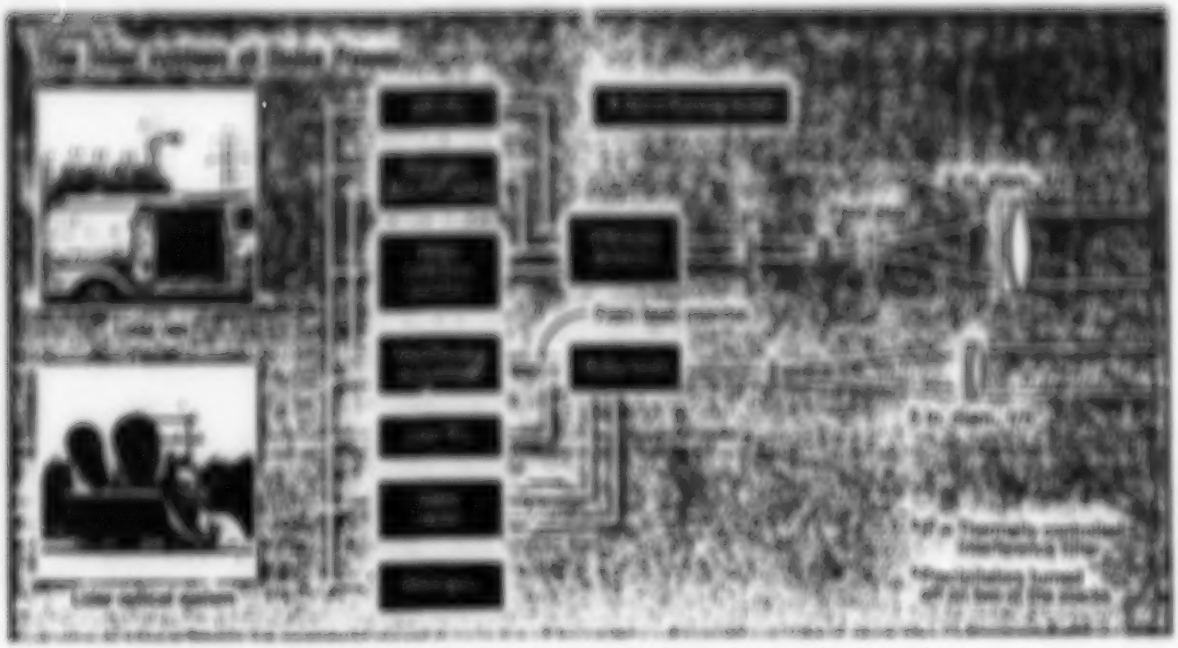
The lidar technique for remote measurement of plume opacity was first demonstrated by Evans (1967) (see Additional reading) who used lidar equipment designed for atmospheric studies. He showed that the opacity and transmittance of a plume could be determined by aiming the laser beam through the plume and comparing the relative backscatter intensity of the beam by the atmosphere in front of and behind the plume. In 1972, a van-mounted lidar designed for plume opacity measurements was developed for EPA by General Electric Company. This system is shown in operating configuration at the Duke Power Plant site in Figure 5. The operating characteristics of the system are given in Table 2.

The accuracy of the lidar was determined by using neutral density screen targets of known opacity. The opacity of 1-m diameter screens was determined by laboratory transmis-

TABLE 2

Mobile lidar systems characteristics

Component	Characteristic
Transmitter	
Laser	Rotating prism, Q-switched ruby
Wavelength	694.3 nm
Pulse width (FWHH)	<30 nanoseconds
Maximum output	1.0 joule
Repetition rate	3 pulses per minute
Cooling	Deionized water
Objective lens	12.7 cm, f/5
Beam divergence	~0.5 milliradian full angle
Receiver	
Objective lens	15.25 cm, f/5
Field-of-view	4 milliradian full angle
Bandpass (FWHH)	1.2 nm
Photomultiplier	IT&T F4084 (modified S-20)
Off-gating	≥60 dB
Response	~100 nanoseconds



someters, which were in turn calibrated by using Kodak Wratten neutral density filters. The lidar opacity measurements of the calibrated targets were made at a distance of 200 m. The results indicated that the lidar is accurate to within 3% opacity for opacities less than 50%. At higher opacities the results showed maximum error of about −15% opacity for a targeted opacity of 100%. This decline in accuracy for opacities is of little concern since no opacity standards for emission sources are above 60% opacity.

A series of measurements were made at he Duke Power Plant site over several years at a range of 400 m to compare the lidar results with those of the instack transmissometer. The comparison showed a high degree of correlation (coefficient 0.993) between the remote lidar measurement and the instack measurement of opacity. However, the remote measurements were higher than the instack measurement by about 3% at the 3% instack opacity level and by about 6% at he 30% opacity level. Interestingly, the correlation would have been almost exact if no adjustment had been made for the stack diameter change at the top of the stack. This discrepancy demonstrates the need for making stack-exit measurements by using instack instrumentation at the stack exist as previously discussed.

Planned activities

The type of measurement that can be made with the MFCS (the "uplooking" perimeter measurement to yield mass-emission rates) has excellent potential for monitoring emissions from extended area sources, where no single stack is generally involved. For this reason the measurement concept is being extended to the infrared spectrum with the development of an "uplooking" GFCR instrument for SO_2 in a plume against the cold sky background. This type of instrument, first described in 1975, has the advantage (over the MFCS instrument) of being able to operate at night and of being applicable to a greater number of pollutants. A comparison of both the "uplooking" GFCR and the MFCS against the Reference Methods at an isolated stack was conducted during the summer of 1976. An LDV system, pibals, and a tethered balloon were used to measure the local wind velocity. The analyses of these data has not yet been completed.

Evaluations of the lidar system are still under way; comparisons are being made with both trained observer and instack transmissometer measurements. Work is being conducted by SRI International to develop a small portable lidar for remote plume opacity measurements that would cost approximately $20 000.

The continued cooperation of Duke Power Co. is gratefully acknowledged. Dr. H. M. Barnes, Mr. K. Foster, Mr. R. Rollins, and Mr. R. White, all of EPA, contributed significantly to various phases of the evaluation programs. Appreciation is also expressed to the contractors participating in the development and evaluations of the remote-sensing instruments, and to NASA for assistance in funding and technical areas in the LDV programs.

Additional reading

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William D. Conner *is a research physicist within the emissions measurement and characterization division of EPA's Environmental Research Laboratory. Mr. Conner has developed some of the fundamental concepts in remote and in situ measurement of particulate matter opacity.*

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